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THE PRINCIPLES OF GLOBAL VIBRATION TESTS OF A STRUCTURE

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A "global method" for defining the vibration modes of complex nonlinear structural elements of aircraft, rockets, and other composite structures, applying analytical Lagrange mechanics calculation methods to practical experiments, is described. This summary method replaces the separate measurement of each resonance curve, by measuring the total of all signals emitted by pickups distributed over the structure to be tested. The vibration modes are displayed on an oscilloscope. The principle of realization of a global or summary response is explained on the typical example of a beam harmonically excited at the natural frequency of flexure, with ten vibration pickups distributed over the structure.

The global method, developed at the O.N.E.R.A., constitutes a doctrine in the study of the vibratory behavior of structures. The method is based on an experimental determination of the structural parameters from harmonic vibration tests. Recent improvements have permitted us to give to these tests known as "global tests", a form adapted to the global method. This permits differentiating these tests from other ground vibration tests, which are increasing in number and variety of form, depending on the result sought.

1. Definition of the Global Method

The "global method", in the sense in which it is understood here, applies

* Numbers in the margin indicate pagination in the original foreign text.

conventional calculation methods, based on analytical Lagrange mechanics, to practical experiments. In his book (Bibl.1), R.Mazet, who recommended this particular method, wrote as follows:

"In most practical cases, the internal contexture of the studied system is not exactly known or is so complex that a detailed calculation of T (kinetic energy), of S (potential energy), or of D (dissipation function) would become extremely time-consuming and of illusory accuracy (inertia moments of complex structural parts, elasticity of principal springs, poorly defined passive resistances). It will then be necessary to use actual experiments for determining the equations of motion, after first having postulated a hypothesis as to the form of these latter."

The method, used here and known as "global method", is a summary method comprising three stages:

1) Accurate determination of the degree of freedom.

2) Selection of the mathematical model.

3) Experimental determination of the coefficients.

In the particular case of vibration problems, the form of the mathematical model is frequently already defined by the contemplated end use of the results, for example, in stability calculations. The actual test thus will have to concern only the determination of the degree of freedom of the object and the definition of the coefficients of the equations of motion.

2. Vibration Tests

The fact that the ONERA* selected the global method as their standard has shifted all difficulties, inherent in calculations from working drawings, to

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actual experimentation. This made improvement of the testing technique necessary, which was facilitated by the general evolution of measuring techniques, and required the development of methods for an experimental determination of the equations of motion.

Numerous papers, published on this subject, indicate that an extrapolation of methods used by electricians to the mechanics of vibrations will not be an easy task.

In fact, the scattering of the numerical data, obtained for certain coefficients, had never been satisfactorily explained. A recent analysis of the vibratory behavior of complex structures showed that the difficulties were less due to the measuring technique itself than to a proper definition of the sought quantities.

a) Definition of the Quantities to be Defined in a Test

The mathematical model is selected in linear form, of the following appearance:

$$\left\{ -\omega^2 \begin{bmatrix} \ddots & & \\ & \mu & \\ & & \ddots \end{bmatrix} + j\omega \begin{bmatrix} \ddots & & \\ & \beta & \\ & & \ddots \end{bmatrix} + \begin{bmatrix} \ddots & & \\ & \gamma & \\ & & \ddots \end{bmatrix} \right\} \cdot \left\{ q \right\} = \left\{ F \right\} \qquad (1)$$

where

$\gamma_i = \omega_i^2 \cdot \mu_i$

$\omega_i = \sqrt{\dfrac{\gamma_i}{\mu_i}}$ = natural frequency;

μ_i = generalized mass;

γ_i = generalized stiffness;

β_i = generalized viscosity.

<u>Note</u>: The condition that the matrix of the values β be diagonal has not been imposed by subsequent calculations but was stipulated by factors encountered in the tests and in the work-up of data.

The column of forces $|F|$ appears in this model since, on the one hand, /58 the stability calculations are always based on coefficients valid for a harmonic motion and since, on the other hand, a definition of the coefficients of the equations of motion [eq.(1)] requires the presence of an excitation, as will be demonstrated below.

The wanted coefficients are the numerical values of μ_i, γ_i, and β_i for the i modes retained in the first phase of the tests, namely, the phase of selecting the degree of freedom, a point which also will be discussed later in the text.

b) Notes on the Structures to be Tested

The selection of the degree of freedom consists in defining the structure to be tested and, after a first experimental phase, selecting the modes to be retained. As typical example, let us use an aircraft: To meet the requirements of the tests, the aircraft must be subjected to conditions practically identical to those in actual flight, which can be obtained by elastic suspension. Consequently, the structure to be tested by the global method must contain the stiffnesses and the masses of the suspension elements. In addition, other masses, stiffnesses, and dissipation forces are introduced by the means of excitation and measurement.

A detailed study of the significance of these factors was made by Försching (Bibl.2) who suggested we compensate for these phenomena; theoretically, this would permit a test on the isolated aircraft.

In practice, however, a total compensation is impossible since the needed device would interfere with the stability; in addition, the six motions of the unit would become inaccessible to the vibration tests.

For this reason, the process of practical compensation was retained by us.

This procedure is based on the principle suggested by the ONERA (Bibl.3, 4), in which the test is performed on the system of aircraft + suspension + compensation device.

With respect to the resultant considerable changes in the structure to be tested, which must be allowed for in the results, the incorporation - in accordance with a suggestion made elsewhere (Bibl.5) - of an electric network for correcting the distribution of the dissipation forces in the unit to be measured, will merely involve a negligible change in the structure.

c) Various Phases of a Test

The various phases of a classical test comprise the following:

1) Definition of the object to be treated and first frequency sweep, for approximately determining the natural frequencies and for identifying the corresponding modes in a given frequency range.
2) Selection of the modes to be retained.
3) Assignment of the excitation forces.
4) Measurement of the coefficients.

Let us note that this testing program has been established by practical experience. The program centers on an individual treatment of the modes in the phases 2, 3, 4. This will seem quite self-evident to the experimenter who has to perform the vibration tests in accordance with the global method; nevertheless, this feature is the one that characterizes the tests and differentiates them most from studies based on electric networks.

By an individual study of each mode, the experiment implicitly takes into account the nonlinearities of the structures. In fact, if the structures were to exhibit linear behavior, a separation of the modes would be a commodity rather than a necessity. It is sufficient to recall that the vectorial response, at a given point of a linear structure as a function of the excitation frequency, despite the complex appearance, is nothing else but the vectorial sum of circles in the case that the matrix $[\beta]$ is diagonal; thus, it is always possible to use the particular responses of different modes, provided that the mathematical equations of these modes are known. Conversely, if the circles are known and graduated as a function of the frequency parameter, the coefficients of the various terms in eq.(1) will also be known. This simplification, which is practically useful but involves protracted work-up of the data, is not always feasible. The reasons (Bibl.6) are as follows:

the already mentioned nonlinearities;

the fact that the distribution of the dissipation forces does not satisfy eqs.(1).

These are also the reasons which require continuation of the individual treatment of the modes - beyond what has been done in classical tests - by supplementing the testing program in two points:

1) Definition of the amplitude of a mode at which the coefficients (varying as a function of the amplitude if the structure is nonlinear) are revealed.
2) Definition of the distribution of auxiliary damping forces, in such a manner that the system of structure + suspension + electric network will constitute a vibrating system whose oscillations can be represented by eqs.(1).

It will be demonstrated below that these two phases can replace others in the classical testing program; the same considerations that have made this complement necessary will lead to modifications in the succession of the other phases.

The test, in its new conception, corresponds to the doctrine established at the ONERA in the field of vibration, i.e., to the global method; we suggest the term "global test" to differentiate it from the entity of various tests that are now grouped under the term of "ground tests".

The expression "global" is justified by the fact that global methods form part of this novel type of testing, which will be described below.

3. Global Test

The three principal phases of the test are already given by the pure and simple definition of "global method". Below, we will retain these phases and indicate, for each phase, the factors that define the purpose of the operation and the testing means used.

a) Definition and Identification of the Degrees of Freedom by Total Sweep and Visual Display

After the mathematical model has been selected, the main purpose of the test will consist in a characterization of the structure. Primarily, the degrees of freedom must be selected, a choice which is guided by the natural frequencies and by the strains.

In general, the stability calculations for aircraft and rockets permit fixing an upper limit for the natural frequencies to be retained. The determination of the degrees of freedom comprises a definition of all natural frequencies in a given frequency range extending from zero to the critical frequency, followed by an identification of the corresponding modes. Among these modes, those entering the calculations must be selected. This automatically eliminates any resonances that do not correspond to a mode of the overall unit and, for example, the resonances of certain structural elements of low inertia (metal skins, connecting rods, etc.).

Nevertheless, these types must also be identified, since they might be of /59 some importance for the fatigue strength; however, they do not enter the mathematical models.

The classical testing procedure is to distribute a large number of pickups over the entire structure, and then to define the response of each individual pickup as a function of the excitation frequency. It is obvious that this method will either give too many data, or not enough data if not all the pickups are used. In fact, the selection must be made in such a manner that any local resonance (for example, that of a control surface) can be detected. In practical application, the electronic equipment becomes extremely cumbersome for the recording of a large number of signals and the work-up time of the data becomes excessively long, which automatically induces the operator to reduce the number of pickups used, specifically for material reasons if the vectorial method is used.

The search for a more rational and more reliable solution will automatically lead to an application of the global method. Instead of separately measuring each resonance curve, the sum of the signals of all pickups is measured, taking the phases into consideration so as to avoid the possibility that signals of equal but out-of-phase moduli of π would cancel out. The technique is explained in Appendix I.

In this method, the number of pickups no longer is limited and a single vectorial curve, which can be obtained with a minimum of instrumentation, permits the detection of even local resonances on a given structural element, provided that a pickup had been placed at this particular point. The time of work-up is reduced in the same proportions.

By using a large number of pickups, it becomes possible to define the mode during the sweep by simultaneous display of the total of responses on the screen of an oscilloscope (Bibl.7, 8).

b) Adaptation of the Structure to the Mathematical Model

We mentioned above that the mathematical model is prescribed and that a complex structure does not always have a contexture such that its motion could be directly described by eqs.(1). It had been suggested to complement the mechanical structure by an electric network and to identify the shape of the latter in such a manner (Bibl.5) that the system of structure + network would satisfy eqs.(1).

Determination of the electric network constants replaces the determination of the prescribed forces, which requires a criterion; the summary measurement directly enters the first of the criteria used, based on a verification of the vibratory behavior of the entire structure in harmonic excitation. Again, the sum of all the signals, or of a portion selected as a function of the deformation line, replaces the response at a single point of the structure, which is considered as a representative of the mode in conventional tests.

The process of assignment of the structure can only be concerned with searching for the optimum approximation, while a final definition of this quantity will always depend on the end use of the resultant response curve. Obviously, a determination of the coefficients requires such preparatory test phases, and it is logical to use, as criterion for the assignment, the form of the response used subsequently for determining the coefficients (Appendix II).

The second criterion does not use the sum of the signals. This criterion is global or total only in the sense in which, by the visual display, the entity of the individual responses is retained for verifying the vibratory behavior in free motion. The principle of this method, which is quite rapid in application, is as follows:

For a mode, excited in phase resonance, the movements of all structural points are synchronous. If the mode is isolated, this synchronous motion must be preserved after stopping the excitation. This is easy to demonstrate by selecting the signal of a given pickup as reference and by producing the Lissajous figures of this signal, together with the signals of the other pickups. The straight lines obtained by definition, for the phase resonance, must be retained after release.

Practical experience will also show whether it might be preferable to use the mean response, obtained from the sum of these signals, as reference signal, i.e., whether to make use of the global method.

c) Determination of the Coefficients by Averaging

The nonlinearities of a given structure, even if quite minor, always have an extensive influence on the response, specifically on the distribution of the frequency parameter ω over the admittance circle (Bibl.6). The only way to eliminate the uncertainties which result in the definition of the natural frequency is to work at a constant displacement amplitude.

In practice, this raises the following question: Which amplitude must be kept constant, considering that no privileged structural point exists?

Theoretically, the question cannot be answered if the presence of modes other than the wanted one is assumed. The already defined sum of all signals yields the maximum response signal for the mode selected and facilitates the compensation of signals of another mode by inversion, thus eliminating this second mode; however, the result depends largely on the placement of the pickups. If the deformation of the perturbation mode is approximately known, the elimination of this mode may be facilitated by using a pickup arrangement such that the response for this mode becomes minimal. In general, we will retain the method, defined above, of taking the sum of all pickup data, while still leaving open the possibility of a selective choice.

With respect to the modulus of the displacement amplitude, the summation is equivalent to an averaging whose quality, as mentioned above, depends on the selection of the pickups but which, in any case, is much better than that of using the signal of a single pickup as reference.

The average of all responses is complemented by application of the vectorial method which permits retaining only those components of the summary response that correspond to the excitation frequency.

A third and final means has to do with the response curves as a function of the excitation frequency. This process consists in describing a circle (admittance curve) or a straight line (impedance curve) through the points of the response curve, by direct smoothing or by using the Gauss method. The utilization of forces in quadrature (Bibl.6) is especially interesting for a simple work-up (Appendix II).

4. Visual Display of the Responses

The visual display is not a distinct phase of the global test; rather, it is the indispensable complement of the various operations.

This visualization has a double role: to enable the operator, at each instant, to check on the vibratory state of the structural unit and to trace the /60 changes produced by the various manipulations as well as to permit monitoring the individual responses of each pickup.

The visual display can be obtained in four different manners, depending on the signal presentation:

1) Visualization of the real and imaginary components of the signal (Bibl.7).

For simple structures or for structural elements, the totality of the points can thus directly yield the deformation.

2) Visualization of the vectors (Bibl.7).

This solution seems quite promising but, in practical use, the fact that the various attributes cannot be sufficiently differentiated on the scope constitutes a considerable drawback. However, it is possible to represent the vectors in a synoptic scheme of the structure.

3) Visual display of the signal samples, as a function of time (Bibl.8).

In the global tests, the usefulness of this method is limited to a control of the pickup operation.

4) Visual display of the Lissajous figures.

This variant is used as a phase criterion in the transitory regime (Bibl.8). Frequently, it satisfactorily replaces a vectorial presentation in control processes. In fact, the response is not subject to the delays introduced into the vectorial presentation by integration circuits.

5. Conclusions

The use of global methods reduces the testing time, facilitates the work-up of data, and increases the accuracy by averaging the results. In addition, the method permits the treatment of responses of a slightly nonlinear structure, at constant mean amplitude.

In its modified form, the global test must satisfy the requirements of the global method.

APPENDIX I

PRINCIPLE OF REALIZING A GLOBAL RESPONSE

Figure 1 gives an example for obtaining the global response of a beam, harmonically excited at the natural fundamental flexure frequency (the exciter

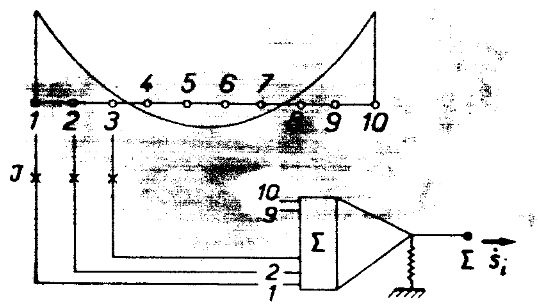

Fig.1 Schematic Diagram of Signal Summation

is not shown). Ten vibration pickups are distributed over the structure.

If the signal of the pickup 1 is taken as reference, its velocity response being in phase with the excitation force, then the signal of the pickup 5 will

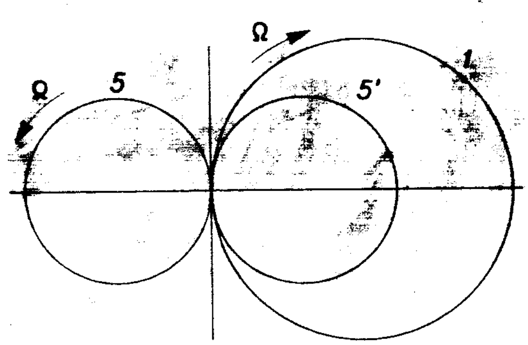

Fig.2
1 - Response of the reference pickup 1;
5 - Response of the pickup 5 before inversion;
5' - Response of the pickup 5 after inversion.

be dephased by π. The signals of the pickups 1 and 5 are partially canceled, if the sum is formed. To prevent this, the sign of all signals, that are not in phase with the reference signal, must be changed. In practical application, the criterion for the commutation results from a vectorial presentation. If the signals of the reference pickup are located in the half-plane to the right of the complex plane, all pickups whose responses are located in the plane to the left will be commuted before addition of the signals (Fig.2).

This operation can be performed by a simple reversal of the pickup wires or by selecting the phase from a phase shifter. This latter solution was used in an electronic device which automatically produced alignment.

APPENDIX II /61

SWEEP WITH FORCE IN QUADRATURE

If, in the classical equation of a system with one degree of freedom and viscous damping, which is a representative model for a mode of

$$\left(jm\,\Omega + \frac{K}{j\Omega} + b\right) \cdot \dot{S} = F \qquad (1)$$

the force F is replaced by

$$F = F_0 \cdot (1 + \lambda j) \qquad (2)$$

we obtain

$$\left(jm\Omega + \frac{K}{j\Omega} + b\right) \cdot \dot{S} = F_0 \cdot (1 + \lambda j) \qquad (3)$$

Considering only the specific cases of excitation for which S and F_0 are in phase, an excitation pulsation Ω will be obtained for each value of λ. This function $\lambda(\Omega)$ yields a modulus $|\dot{S}|$ which is constant and independent of λ in view of the fact that, for satisfying eq.(3), it is necessary that the two real and imaginary parts are always satisfied.

From this it follows that

$$b\cdot\dot{S} = F_0$$
$$|\dot{S}| = \frac{|F_0|}{b} = \text{const.} \qquad (4)$$

On the other hand, the terms on the right-hand side of eq.(3), in the complex plane, yield a straight line parallel to the axis of imaginaries, with

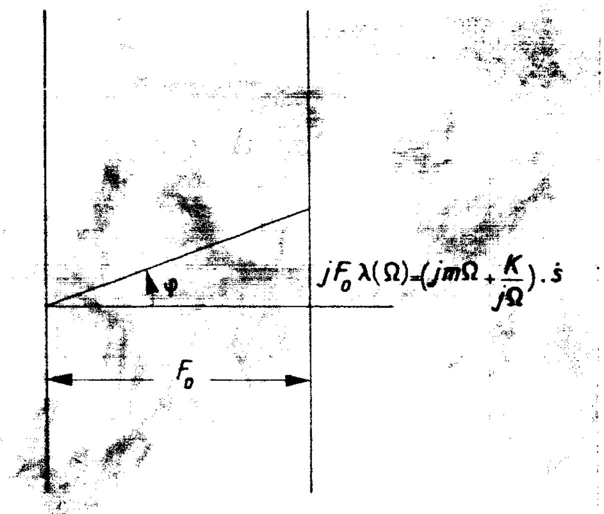

Fig.3

the parameter Ω

with

$$2\alpha = \frac{b\cdot\omega_0}{K}; \quad \omega_0 = \sqrt{\frac{K}{m}}; \quad \eta = \frac{\Omega}{\omega_0},$$
$$\lambda(\eta) = \frac{\eta^2-1}{2\alpha\eta} = \tan\varphi. \qquad (5)$$

From this we find that an application of forces in quadrature represents a sweep in Ω or η, with a constant velocity modulus. For low values of α, this latter condition can replace the rigorous condition of the constant displacement modulus for a structure, since the variations in Ω are negligible for the sweep to be effected.

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